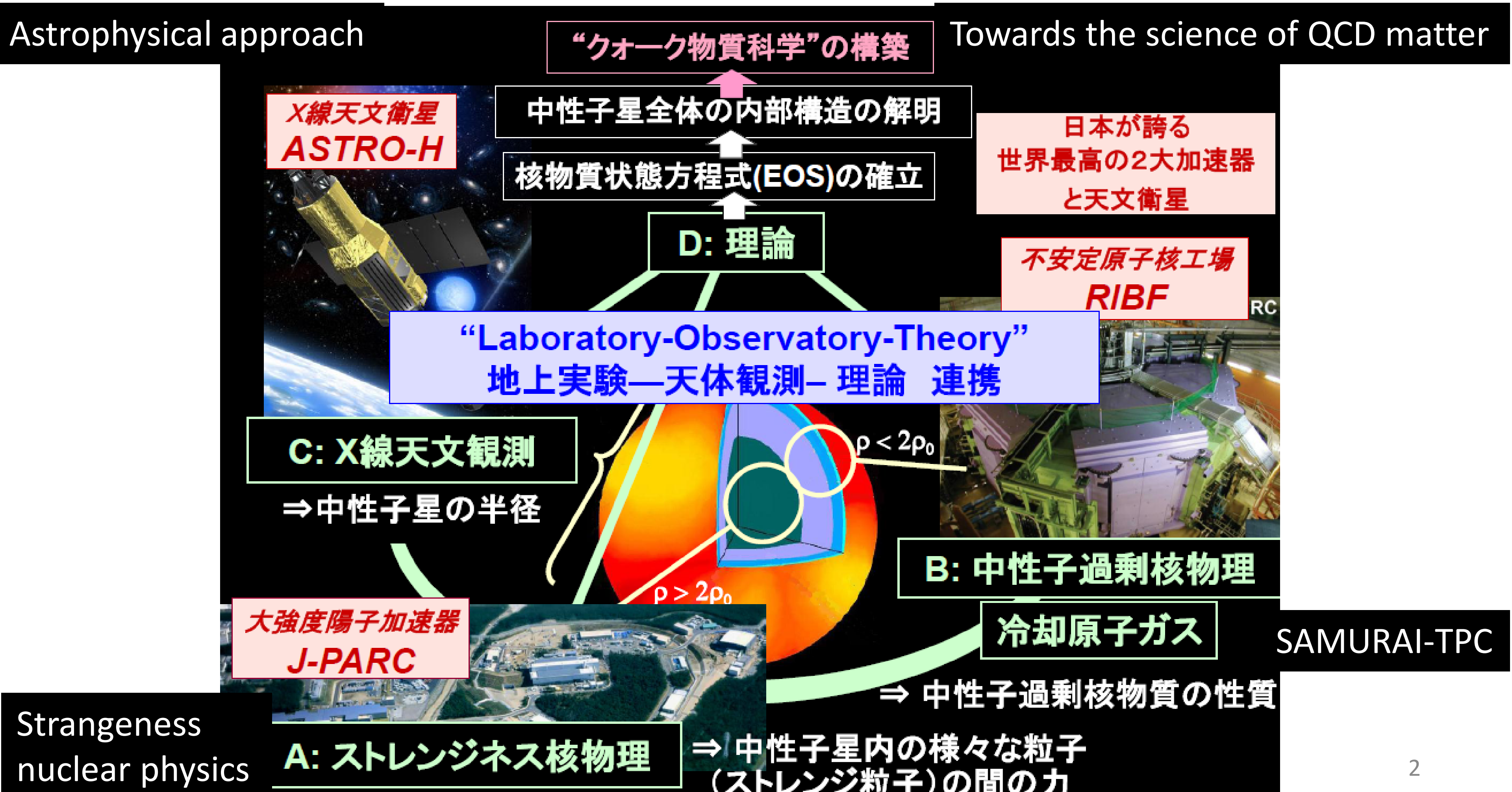
理研RIBFにおける重RI衝突を用いた対称エネルギー密度依存性の研究

Tadaaki Isobe (RIKEN)

実験と観測で解き明かす *中性子星*の核物質

- The study of neutron star matter is elected as ”Grant-in-Aid for Scientific Research on Innovative Areas” five year project.



Primary Physics Goal:

Constrain the Nuclear Asymmetry Energy

$$E(\rho, T=0, \delta) = \varepsilon(\rho, \delta=0) + S(\rho)\delta^2$$

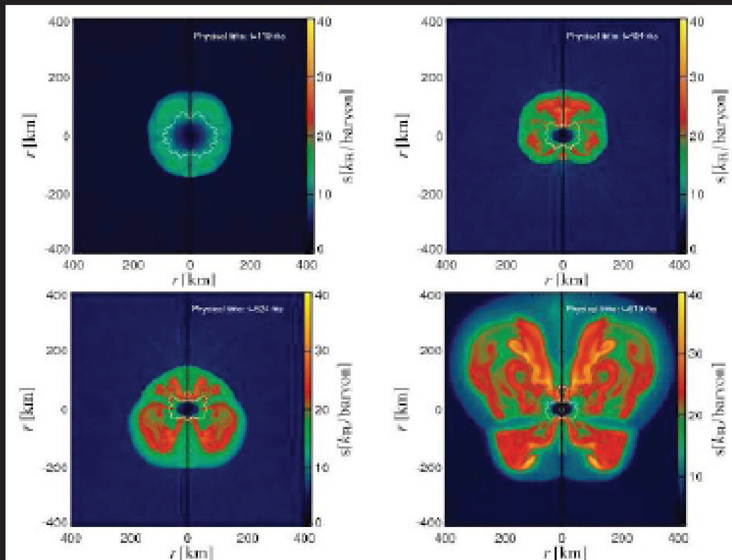
Nuclear equation of state | Well known through experiments | Asymmetry energy

- δ=(N-Z)/A
- **3** important motivation to study asymmetry energy
- Nuclear structure
  - Sustain neutron rich matter of heavy ions/super heavy ions.
  - Information for beyond the super heavy elements?
- Supernovae process
  - In terms of understanding of supernovae explosion dynamics, EoS, neutrino interaction, and electron capture process are important.
- Neutron star structure
  - Sustained by asymmetry energy → neutron star radius depends on asymmetry energy
- Gravitational wave

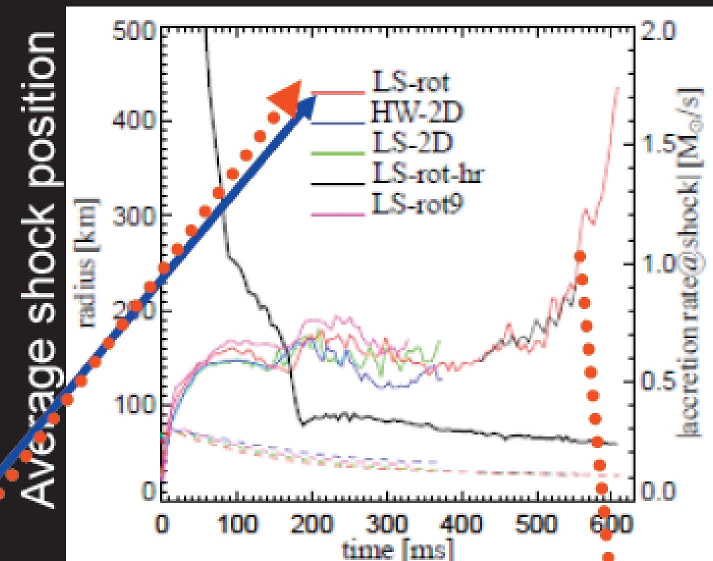
2D neutrino-driven explosion (Garching):

K. Kotake
NuSYM

Marek and Janka (09)
(Ray-by-Ray accurate Boltzmann transport)

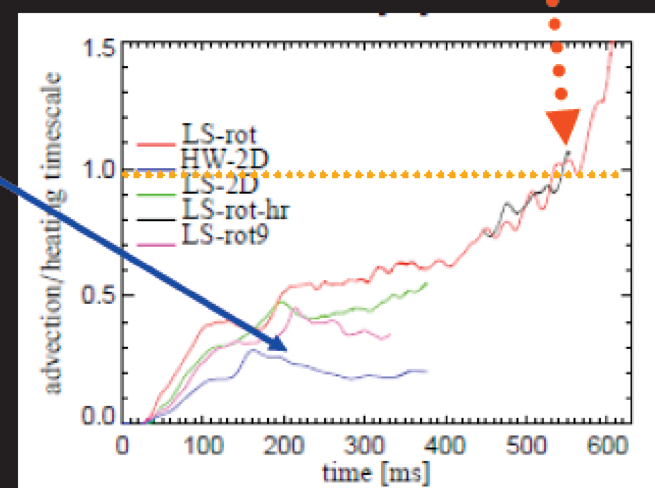


(15Ms by Woosley & Weaver (95))



EOS table

		K(MeV)
• Wolff-Hillebrandt	Hillebrandt et al. 1984, AA	263
• Lattimer-Swesty EOS (LS) — Based on liquid drop model	Lattimer Swesty, 1991, NPA	180
• Relativistic EOS (Shen) — Based on RMF(relativisitic mean field) + Thomas Fermi	Shen et al., 1998, NPA, PTP	281
• Nuclear experiment	Shlomo et al. (06)	240±20



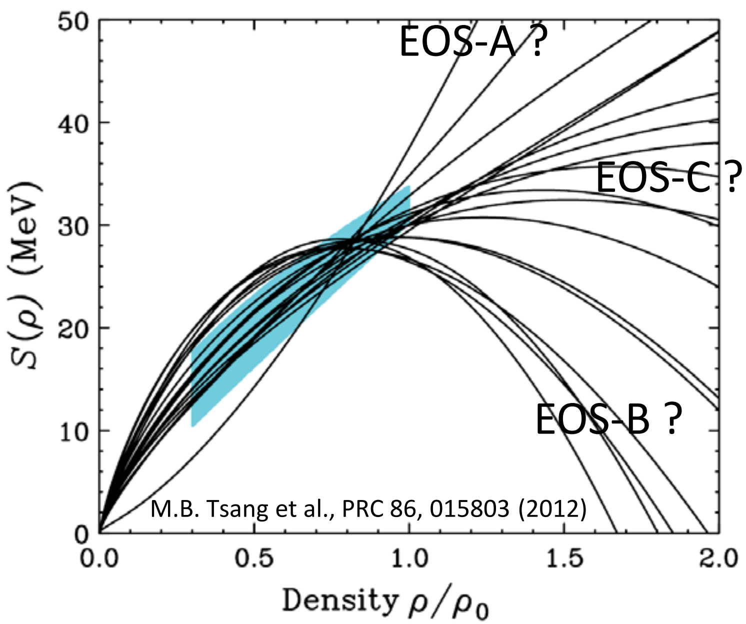
✓ The first success of neutrino-driven exp. in 2D

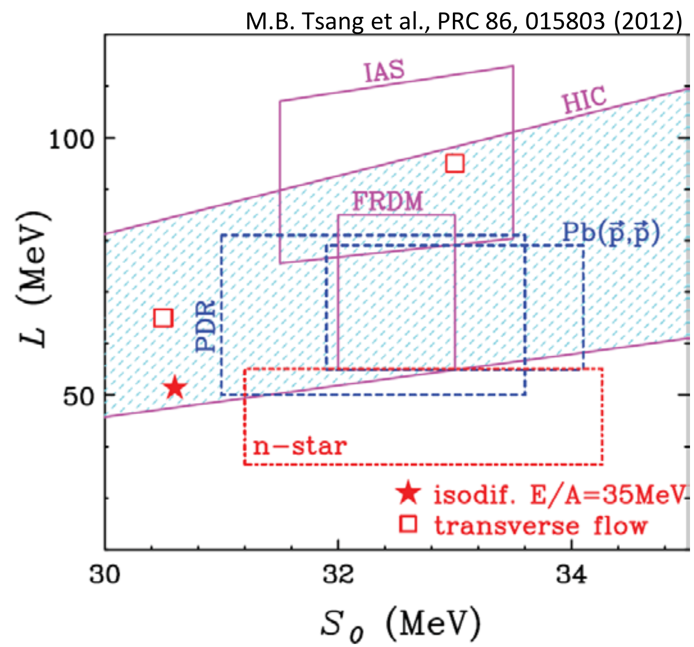
✓ Weak explosion (~10^{50}erg) at the end of simulations. (1-2 orders of magnitude less than obs.)

✓ only for a softer EOS. (Accurate nuc

Density dependent S(ρ) for Z/A: 0.3~0.34

Largest uncertainty:
Density dependence of the asymmetry energy



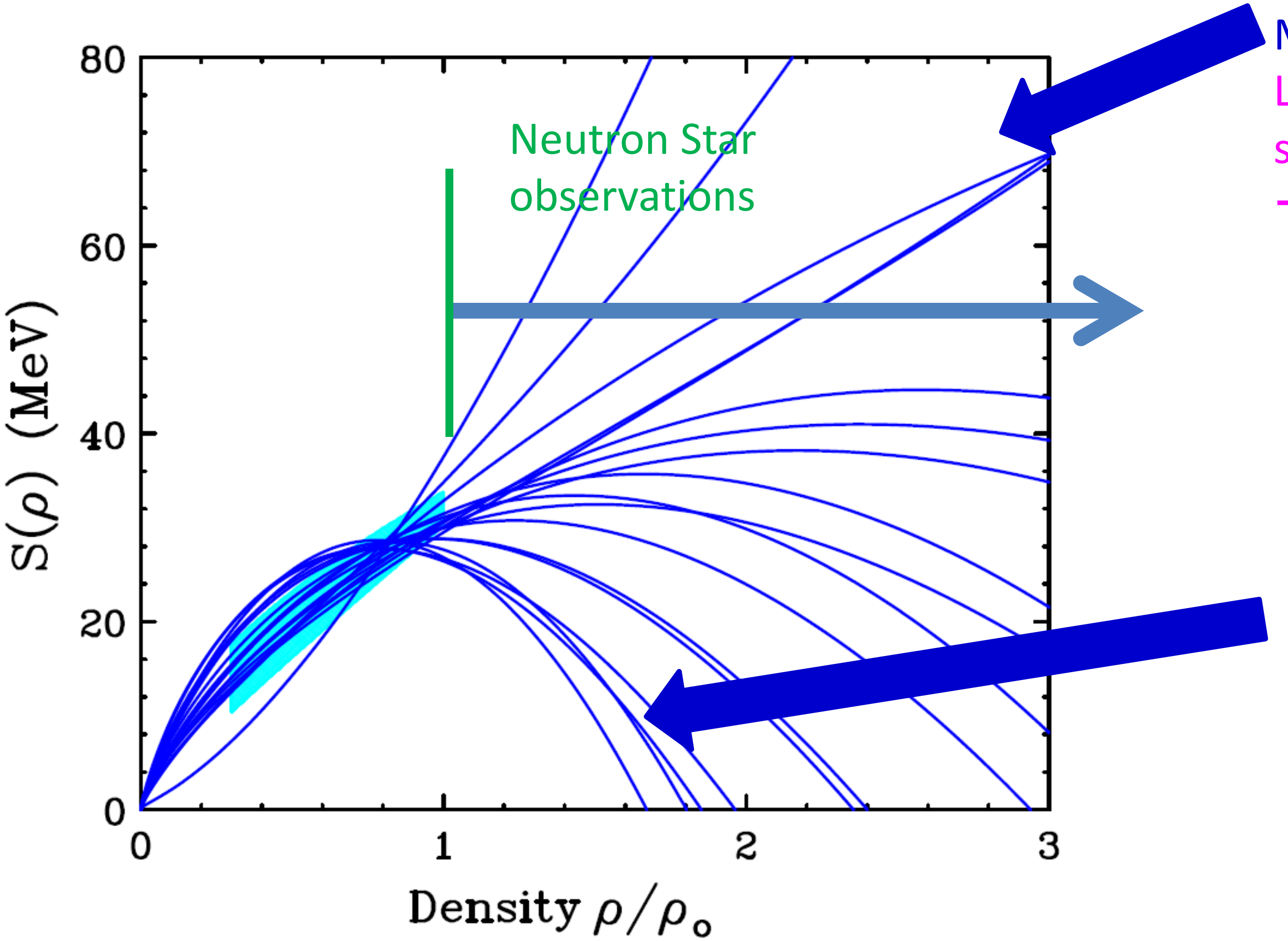


<u>Constrained only around ρ_0</u>

$$S_0 = E_{sym}(\rho_0)$$

$$L = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial \rho}\right|_{\rho=\rho_0}$$

Surprising observations of Neutron Stars



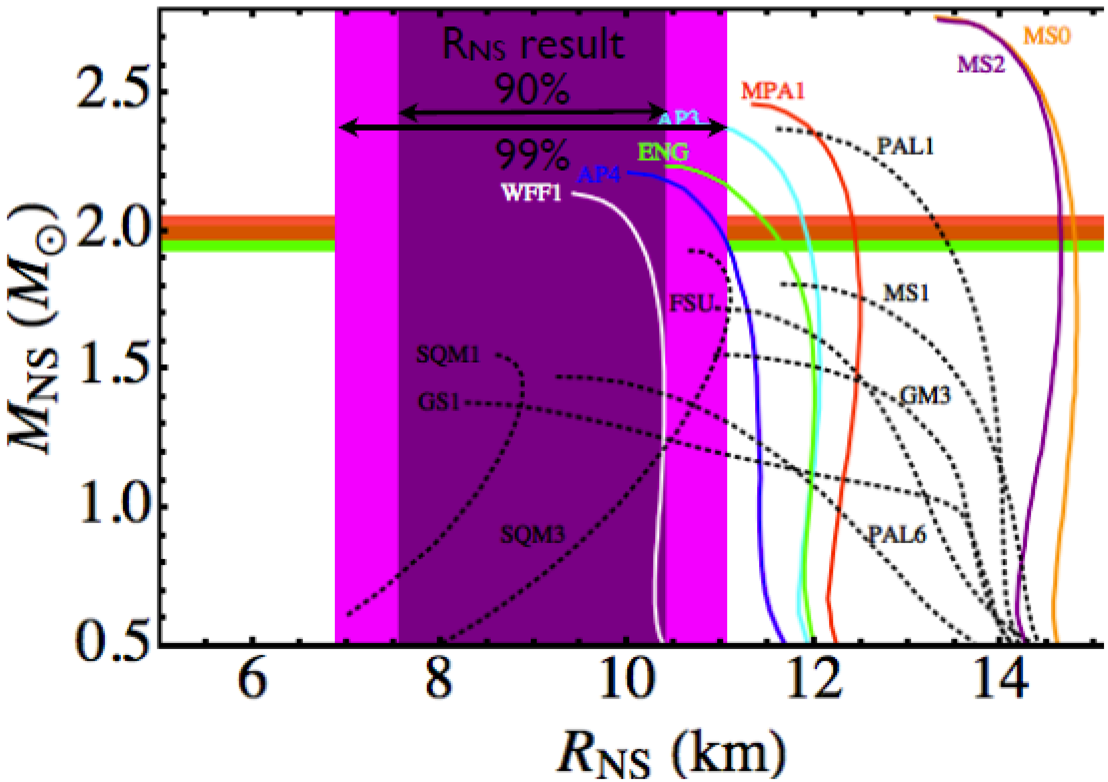
M_{NS} ~ $2M_{sun}$ →
Large E_{sym} or
stiff EoS at high ρ
→ large radius

APJ 772, 7 (2013)

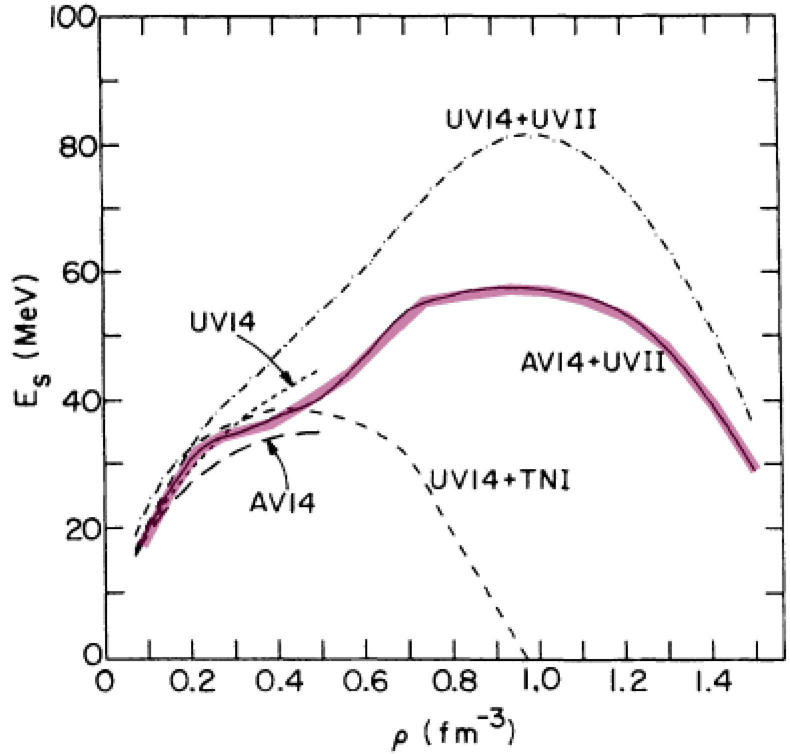
R_{NS} ~ 9 km →
Small E_{sym} or
Soft EoS at ~$2\rho_0$
→ Small mass

Neutron star

Neutron star (Gulliot et al.) qLMXB
APJ 772, 7 (2013)



AV14+UVII ;
Wiringa, Fiks, & Fabrocini ,
Phys. Rev. C 38, 1010 (1988)



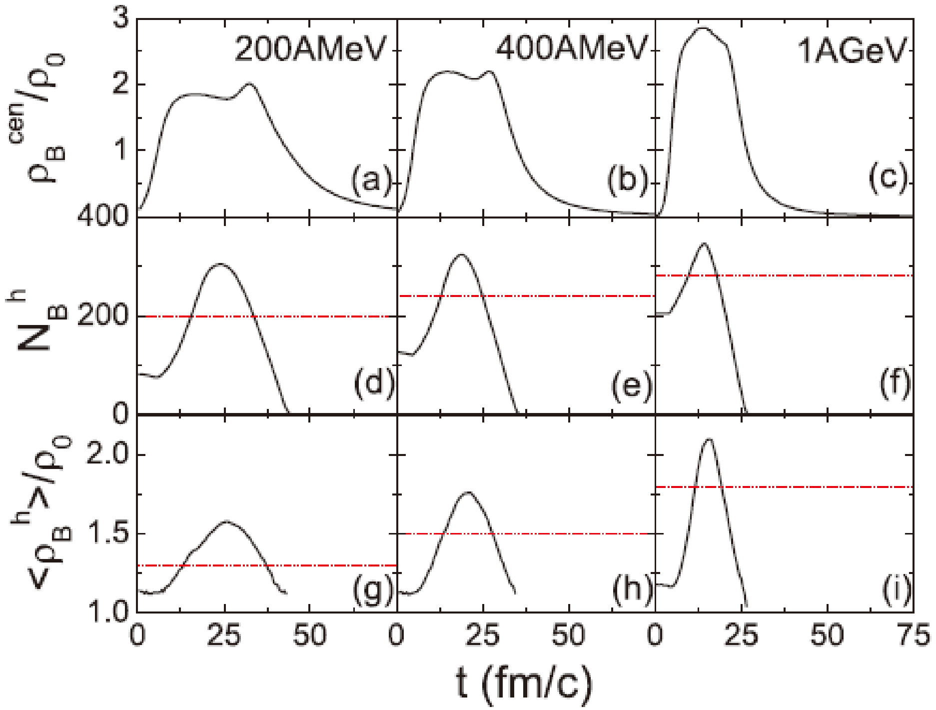
Observation:
$M_{NS} \sim 2M_{sun}$
$R_{NS} \sim 9$ km

Equation of State
softening EoS at $\rho \sim 2\rho_0$
stiff EoS at high ρ

Probing high dense region with HIC

Heavy Ion Collision is unique method to make dense matter in lab..

Au+Au PRC87 (2013) 067601



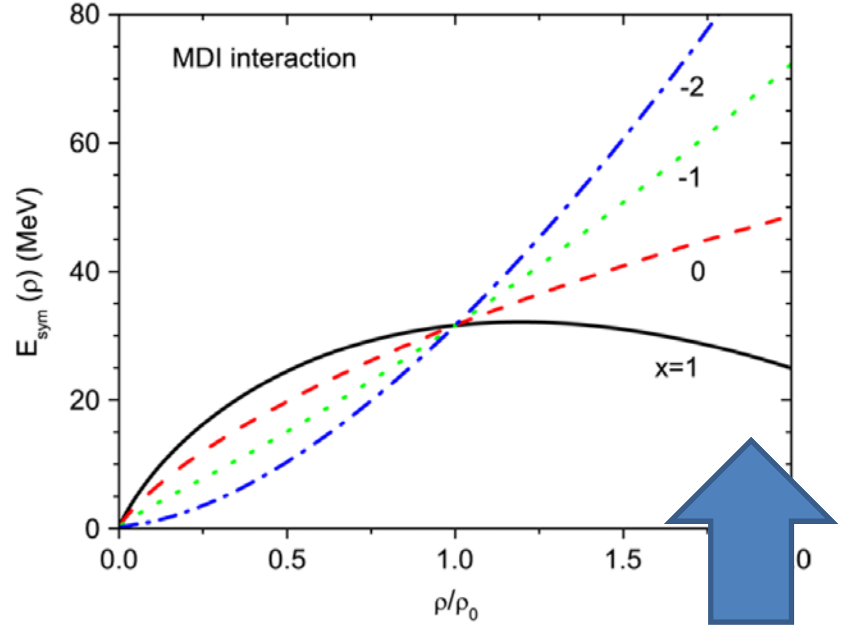
HIC→Dynamics→EOS

- Necessary to understand heavy ion collision dynamics to extract the information related to the EOS.
- BUU and QMD is major transport model for the description of HIC.
  - Still controversial.
  - Numerical results on flow are consistent among the models.
  - Large difference shown in time evolution of density.

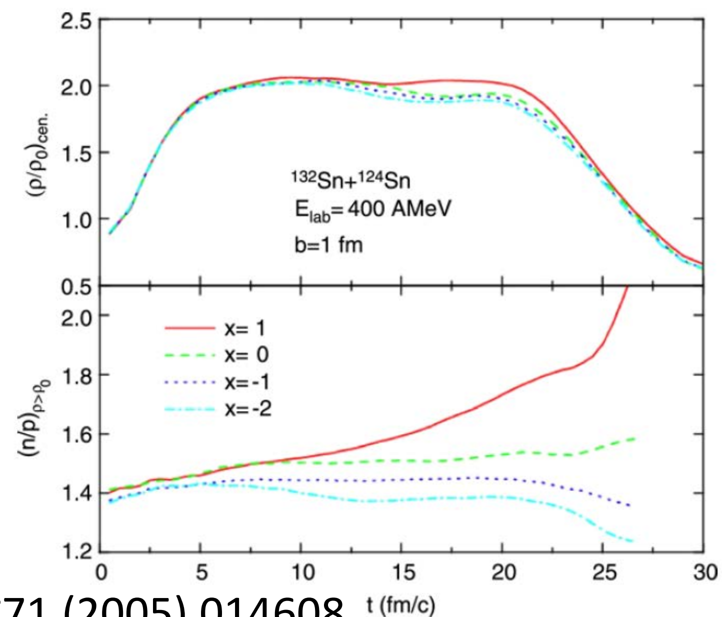
Heavy Ion Collision experiment at RIBF for EoS study

- Esym at N>Z, $\rho > \rho_0$
  - Change both asymmetry and density.
- At the energy of RIBF, **$\rho \sim 2\rho_0$** is expected to be achieved.
- Systematic study of nuclear effect in HIC by changing Z and N.
  - Useful to control coulomb effect.

Phys. Rev. Lett. 94 (2005) 032701



RIKEN-RIBF region



PRC71 (2005) 014608

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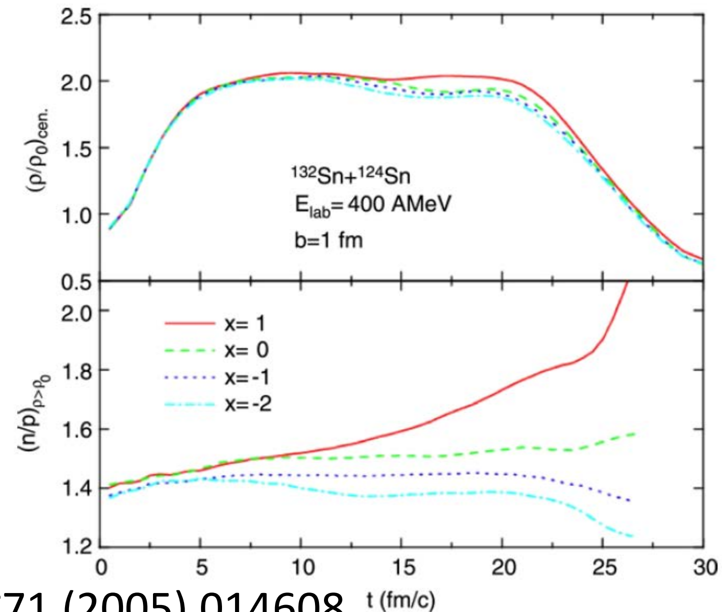

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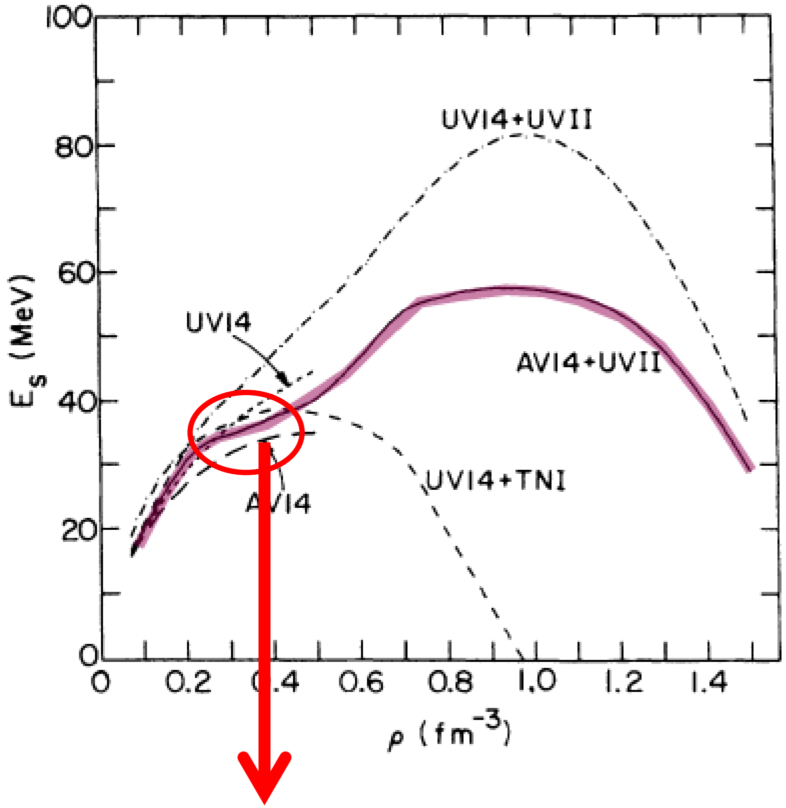
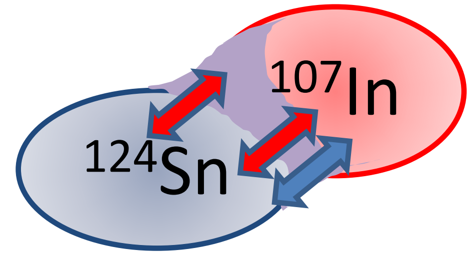


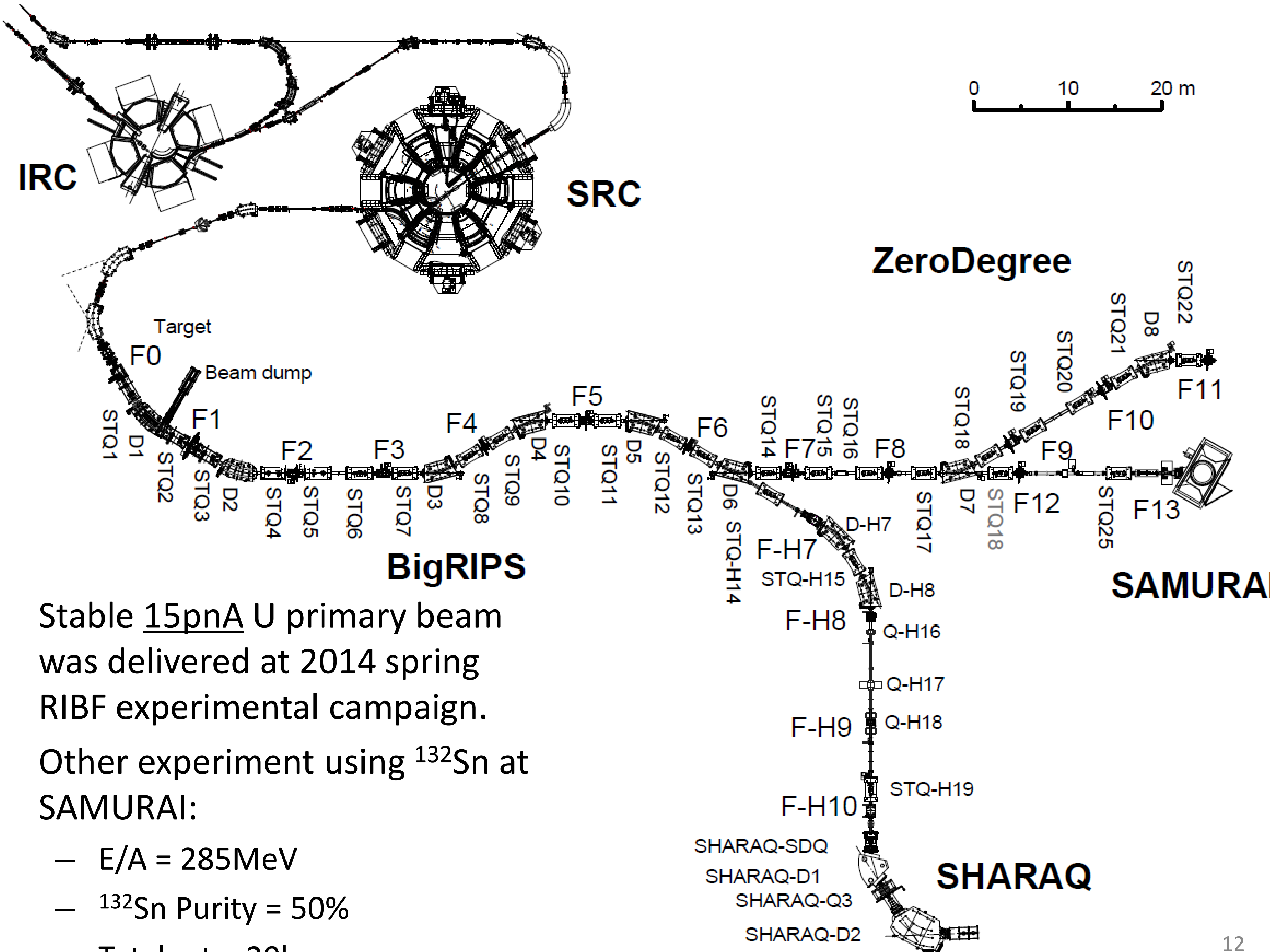
Goal is to decrease the factor of 2 uncertainty in symmetry pressure at $\rho \approx 2\rho_0$.

Heavy RI collision experiment at RIBF

- Isospin diffusion experiment
  - ^{107}In + ^{124}Sn, E/A=50MeV
- Higher energy HRIC at RIBF
  - To study $\rho \sim 2\rho_0$ region.
  - Approved, under preparation



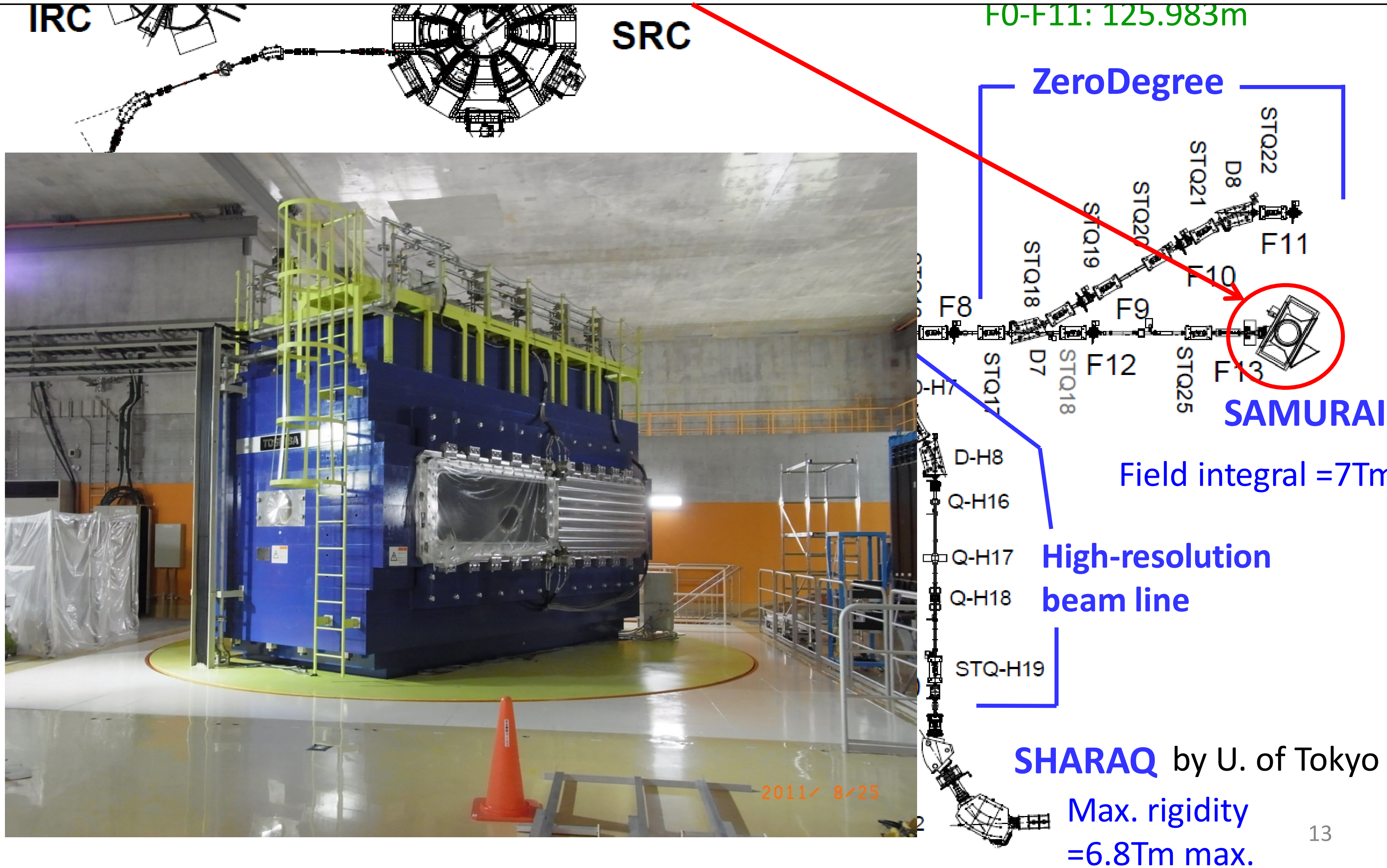
Primary	Beam	Target	E_{beam}/A	δ_{sys}	Goal	Days
^{238}U	^{132}Sn	^{124}Sn	300	0.22	Probe maximum δ	3
	^{124}Sn	^{112}Sn	300	0.15	Probe intermed. δ, σ_{nn}, σ_{np}	3
^{124}Xe	^{108}Sn	^{112}Sn	300	0.09	Probe minimum δ	3
	^{108}Sn	^{124}Sn	300	0.15	Probe intermed. δ, σ_{nn}, σ_{np}	3



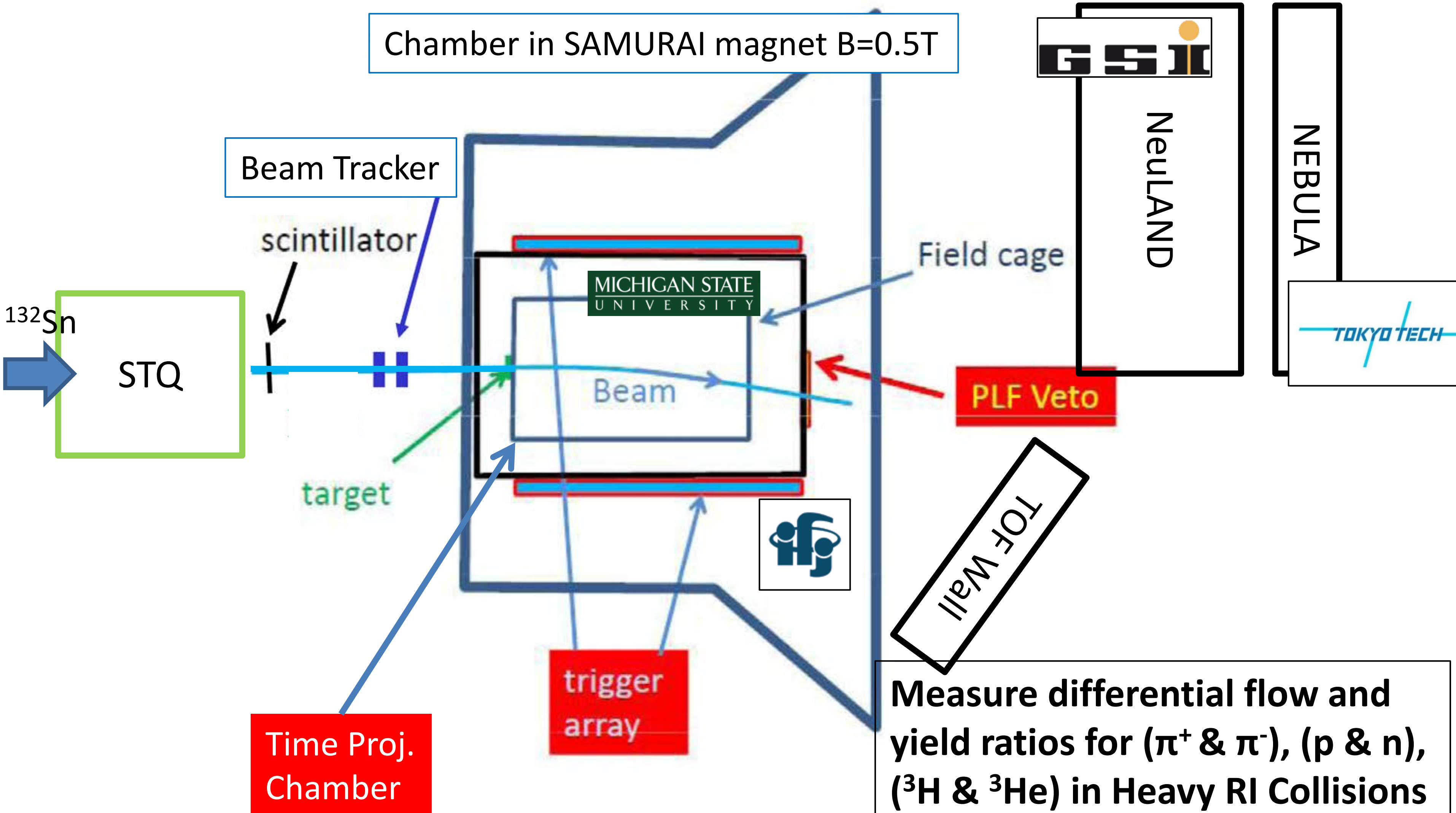
- Stable <u>15pnA</u> U primary beam was delivered at 2014 spring RIBF experimental campaign.
- Other experiment using ^{132}Sn at SAMURAI:
  - E/A = 285MeV
  - ^{132}Sn Purity = 50%
  - Total rate: 20kcps

SAMURAI Spectrometer

Superconducting Analyzer for Multi particles from Radio Isotope Beams



Experimental setup (under construction)



Measure differential flow and yield ratios for (π^+ & π^-), (p & n), (^3H & ^3He) in Heavy RI Collisions at E/A=200 and 300MeV

SPiRIT Collaboration (2009~)

SAMURAI Pion Reconstruction and Ion-Tracker

RIKEN : T. Isobe, M. Nishimura, H. Baba, H. Otsu, K-I Yoneda, H. Sato, Y. Nakai, S. Nishimura, J. Lee, H. Sakurai, He Wang, N. Fukuda, H. Takeda, D. Kameda, H. Suzuki, N. Inabe, T. Kubo, Y. Shimizu

Kyoto Univ.: T. Murakami, N. Nakatsuka, M. Kaneko

MSU: W. Lynch, M.B. Tsang, S. Tangwancharoen, Z. Chajecki, J. Estee, R. Shane, Jon Barney, Z. Chajecki, P. Palni

TAMU: A. Mchintosh, S. Yennello, M. Chapman

Liverpool/ Darsbury: M. Chartier, W. Powell, J. Sampson, R.Lemmon

TITech: T. Nakamura, Y. Kondo, Y. Togano

Korea Univ.: B. Hong, G. Jhang

INFN: G. Verde, P. Russotto

Tsinghua Univ.: Z. Xiao, R. Wang

Lanzhou: Z. Sun

CEA: E. Pollacco

INP: J. Lukasik, P. Pawlowski

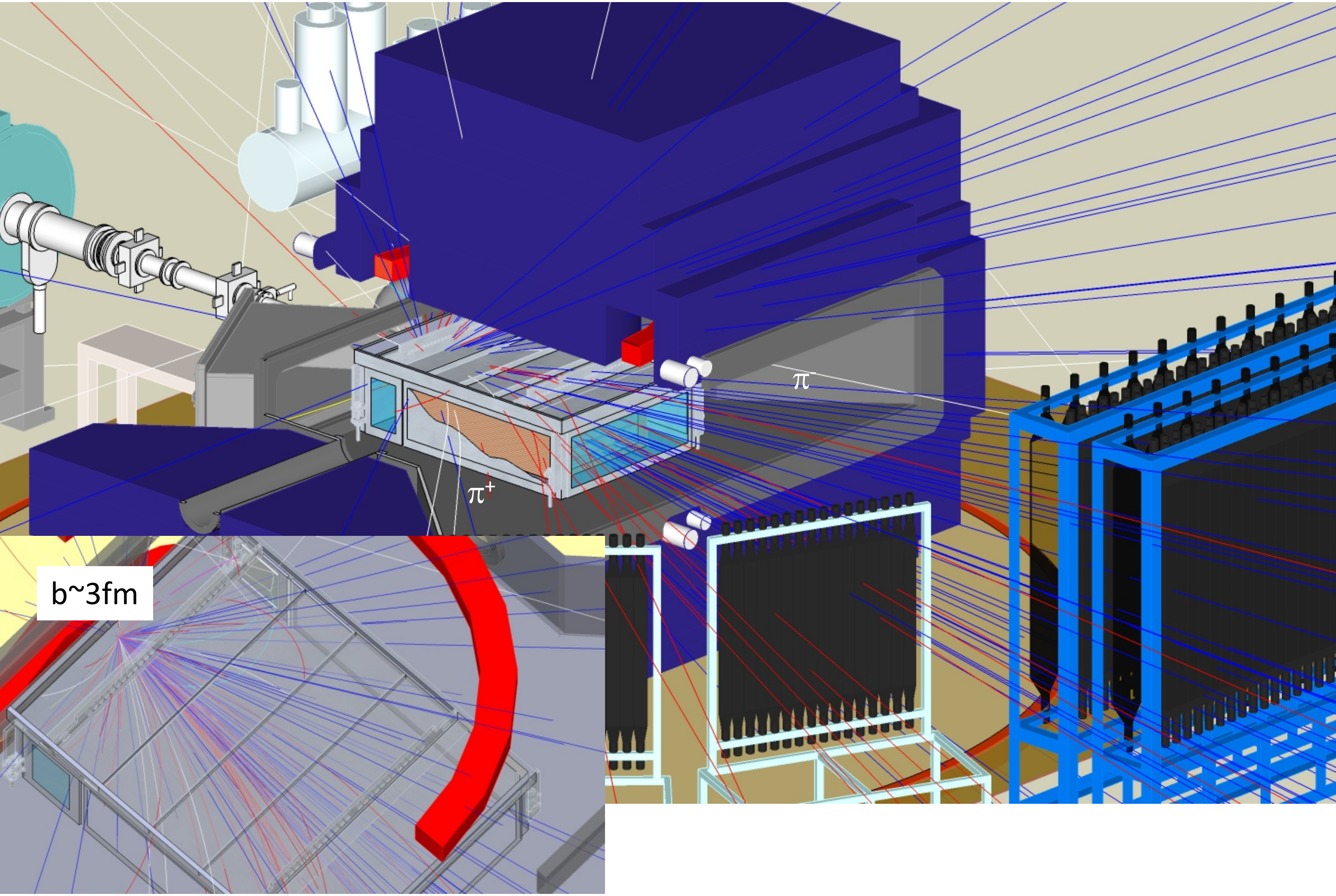
ORNL: A. Galindo-Uribarri

Tohoku Univ.: T. Kobayashi

Rikkyo Univ.: K. Ieki

GSI: T. Aumann

$^{132}Sn+^{124}Sn$ E/A=300MeV



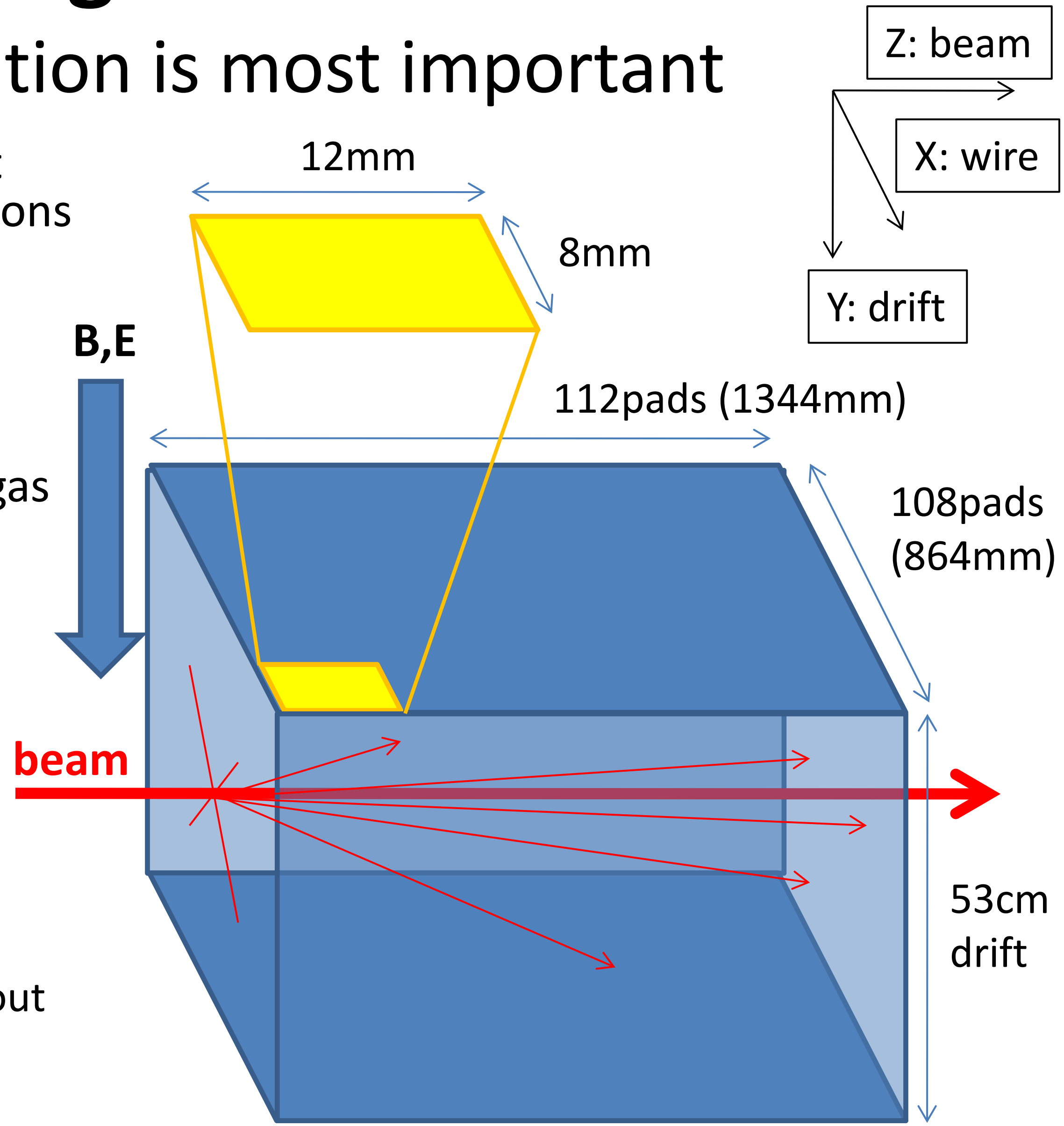
Basic design of chamber

stable operation is most important

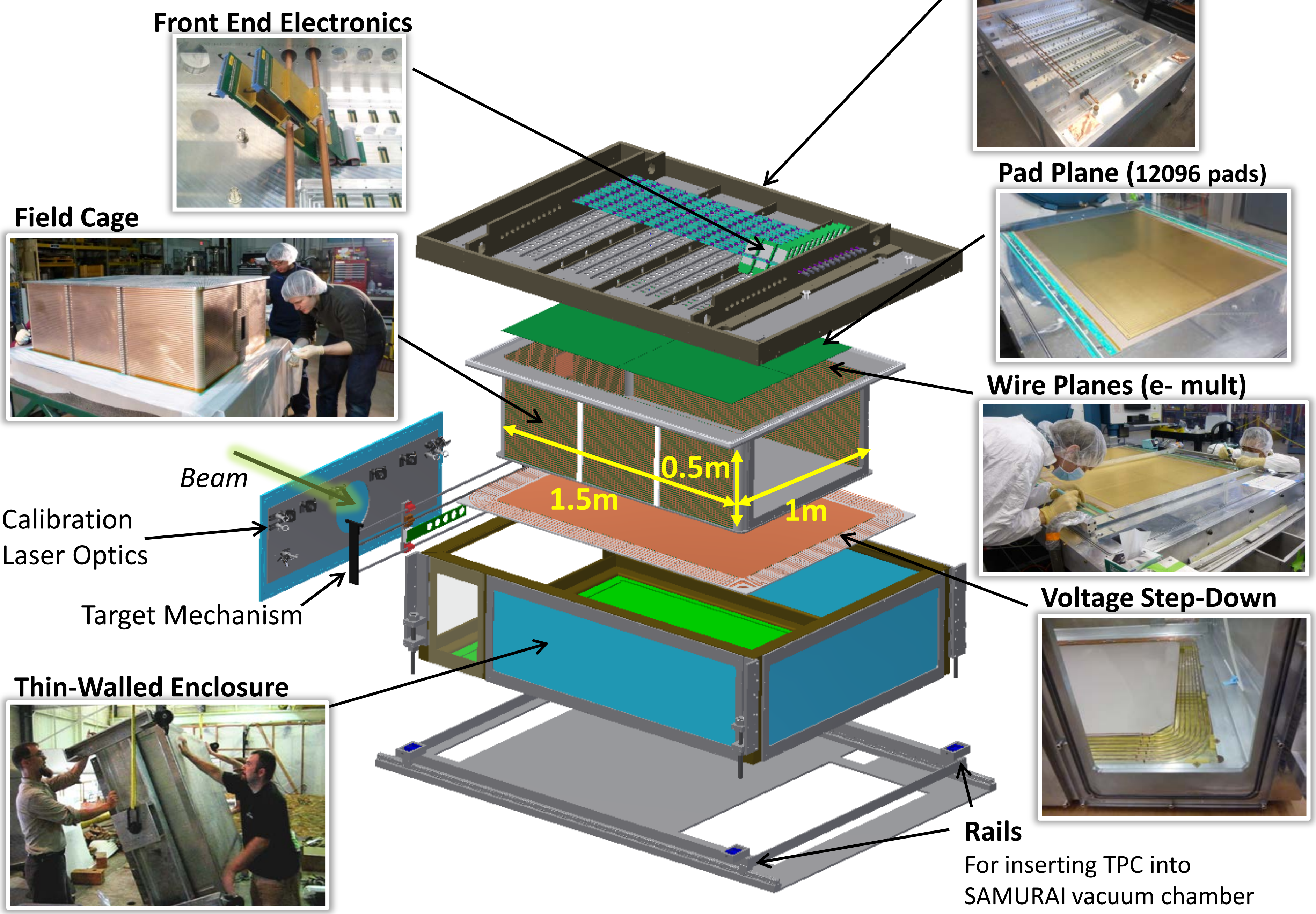
- For the measurement of light charged particles: pions, protons and light ions. <u>Beam passes through chamber as well.</u>

- Based on Bevalac EOS TPC.
- Wire amplification with P10 gas (1atm).
- Target at the entrance of chamber.
- Readout with ~12000 pads.
- 2 track separation: 2.5cm
- Multiplicity: 10~100

- Readout with GET system
  - 12bit high throughput readout

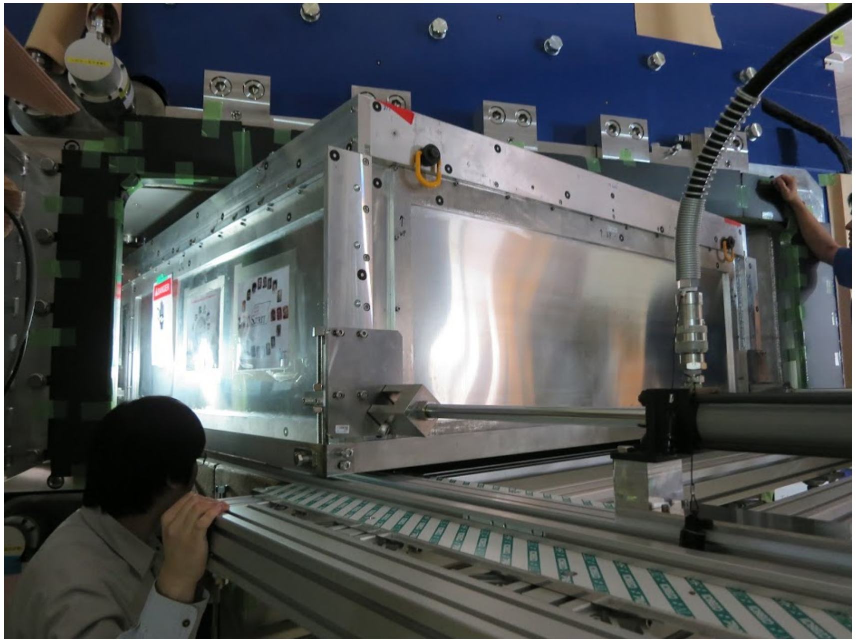


SAMURAI TPC: Exploded View



came to RIKEN at February 2014

Under preparation at RIKEN towards first experiment at 2015



Date	Item
2014-Jul.	TPC installation test into SAMURAI chamber Test under 0.5T magnetic field
2014-Sep.	Mount all of electronics on TPC Readout of cosmic events with GET
2014-Nov.	Electronics and Trigger beam test at HIMAC
2014-Dec./Jan.	Start the preparation of day one experiment

Neutron detector: NeuLAND+NEBULA

NEBULA

- 1scintilator: 180cm x 10cm x 10cm
- 4layer w/ 120 Neutron counters
- 12 VETO counters for every 2 layers
- Detection efficiency~40% for 1n
- Front acceptance: 3.6m (H) x 1.8m (V)

NeuLAND

Come to RIKEN at the end of 2014

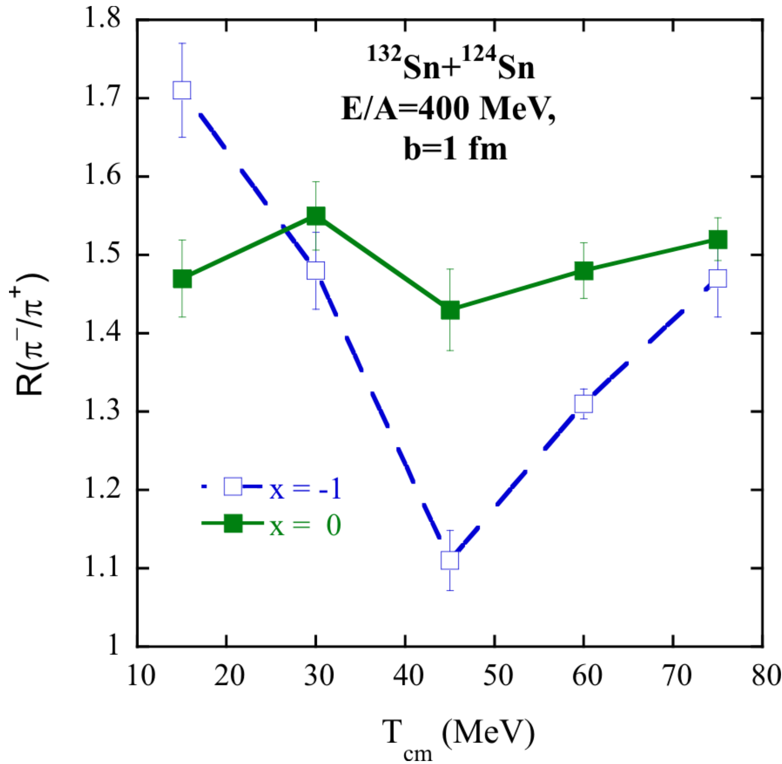
- Tracking type neutron detector
- 1scintilator: 250cm x 5cm x 5cm
- Front acceptance 250cm x 250cm w/ 50 bars
- Depth: 3m with 60 layers

What we are going to measure with SPiRIT

- To study the symmetry energy of high dense region with HIC, we need to understand the HIC dynamics.
- Need multiple observables to constrain theoretical inputs to the transport theoretical calculation.

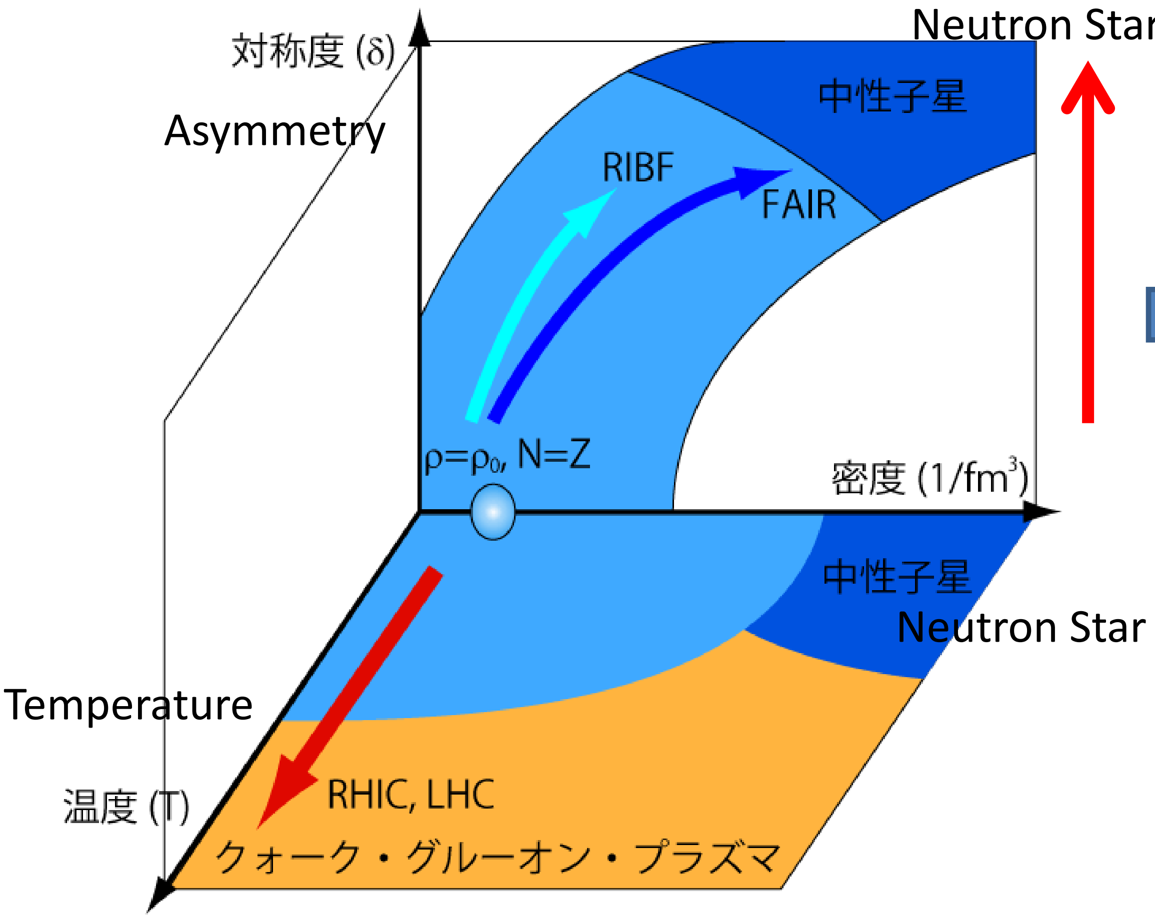
- Charged particles
  - Charged pions, protons, and light ions.
  - Identified with dE/dX – track rigidity.
  - Momentum can be reconstructed.
- Neutrons
- Event characterization
  - Impact parameter, reaction plane →flow

Yong et al., PRC 73, 034603 (2006))



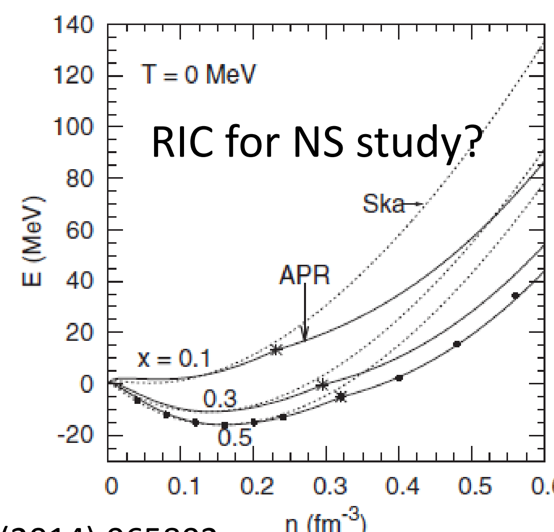
- Charged pion ratio, p/n ratio, ^{3}He/t ratio
- <u>Symmetry energy</u>
- <u>Both the **momentum** and **density** dependencies</u> of the isovector potentials ← p/n ratio, different energy.

さいごに



It was difficult to change.

Subjects for RIBF



PRC89 (2014) 065802